

An elusive radio halo in the merging cluster Abell 781?

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ABSTRACT

Deep radio observations of the galaxy cluster Abell 781 have been carried out using the Giant Metrewave Radio Telescope at 325 MHz and have been compared to previous 610 MHz observations and to archival VLA 1.4 GHz data. The radio emission from the cluster is dominated by a diffuse source located at the outskirts of the X-ray emission, which we tentatively classify as a radio relic. We detected residual diffuse emission at the cluster centre at the level of $S_{325\text{ MHz}} \sim 15\text{--}20\text{ mJy}$. Our analysis disagrees with Govoni et al. (2011), and on the basis of simple spectral considerations we do not support their claim of a radio halo with flux density of 20–30 mJy at 1.4 GHz. Abell 781, a massive and merging cluster, is an intriguing case. Assuming that the residual emission is indicative of the presence of a radio halo barely detectable at our sensitivity level, it could be a very steep spectrum source.

Key words: radiation mechanisms: non-thermal - galaxies: clusters: general - galaxies: clusters: individual: Abell 781 - radio continuum: general

1 INTRODUCTION

Cluster major mergers are among the most energetic phenomena in the Universe. They release a total energy of the order of $10^{63} - 10^{64}$ erg, and it is nowadays accepted that they are the key ingredient to explain the origin and rarity of radio halos in galaxy clusters: shocks and turbulence are generated during such energetic events, and they deeply affect the thermal and non-thermal properties of the intra-cluster medium (ICM).

Radio halos are the signposts of the non-thermal components in galaxy clusters. They are diffuse radio sources, whose size and morphology are similar to those of the underlying hot ICM (e.g. Ferrari et al. 2008, Cassano 2009 and Venturi 2011 for recent reviews). Their spectrum (defined as $S \propto \nu^{-\alpha}$) is steep, with typical values of the spectral index α in the range 1.2–1.4. However, recent high-sensitivity low frequency imaging led to the discovery of radio halos with much steeper spectra (Venturi 2011), with spectral index $\alpha \sim 1.8 - 2$ (e.g. A 521, Brunetti et al. 2008, Dallacasa et al. 2009; A 697 Macario et al. 2010).

Combined radio and X-ray studies provide strong support to the idea that radio halos are found only in unrelaxed

clusters. Buote (2001) first showed a correlation between the 1.4 GHz radio power of halos, $P_{1.4\text{ GHz}}$, and the dipole power ratio P_1/P_0 in the hosting cluster; based on *Chandra* temperature maps, Govoni et al. (2004) found evidence for merging activity in clusters with radio halos. Venturi et al. (2008, hereinafter V08) showed that all radio halos in the GMRT (Giant Metrewave Radio Telescope) radio halo survey are located in clusters with signs of dynamical disturbances.

More recently, Cassano et al. (2010, hereinafter C10) carried out a quantitative analysis of the radio halo–cluster merger scenario. They used all clusters in the GMRT radio halo cluster sample (Venturi et al. 2007, hereinafter V07, and V08) with available high quality *Chandra* images (a total of 32 clusters) to characterize the presence of substructures by three different methods. They showed that clusters with and without radio halos are well segregated according to all parameters indicating substructure: radio halos are associated with clusters currently undergoing a merger, while clusters without radio halo are usually more “relaxed”. Four clusters, however, are noticeable outliers in the correlations, being disturbed systems with no detectable radio halo at the sensitivity limit of the 610 MHz GMRT survey (V07 and V08). One of the outliers, Abell 781 (hereinafter A 781), has been observed by us with the GMRT at 325 MHz in a low

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frequency follow-up project of the GMRT radio halo survey (Venturi et al. to be submitted). In this letter we report on our study on A 781 and discuss the results in the light of the scenario of merger-induced formation of radio halos.

We adopt the Λ CDM cosmology with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$. At the redshift of A 781 ($z=0.2984$), $1'' = 4.404 \text{ kpc}$.

2 A 781 AND ITS RADIO EMISSION

A 781 ($\text{RA}_{\text{J}2000} = 09^h 20^m 23.2^s$, $\text{DEC}_{\text{J}2000} = +30^\circ 26' 15''$, $z=0.2984$) is known to host a diffuse radio source South-East of its centre, tentatively classified as a relic on the basis of GMRT 610 MHz observations (V08).

The X-ray luminosity of the cluster, reported in the NORAS survey, is $L_{[0.1-2.4\text{keV}]} = 4.6 \times 10^{44} \text{ erg s}^{-1}$ (Bohringer et al. 2000). This value is 3 times lower than in the BCS catalogue (Ebeling et al. 1998 and 2000) – our reference in the selection of the GMRT radio halo sample – and it is in line with measurements based on recent Chandra observations (Maughan et al. 2008, Wittman et al. 2006), and derived from a shallow ROSAT HRI exposure (S. Ettori, private communication). The X-ray brightness distribution is very complex, with multiple peaks in the central region, and a secondary south-eastern condensation at $\sim 7'$, associated with the galaxy cluster CXOU J 092053+302800 located at $z=0.291$ (Geller et al. 2005). The candidate radio relic is located at the border of the X-ray emission from A 781, in the direction of CXOU J 092053+302800 (see Fig. 5 in V08).

2.1 The radio observations

The cluster was observed with the GMRT at 325 MHz in January 2007, as part of a project devoted to a low frequency follow-up study of all radio halos and relics belonging to the GMRT radio halo survey (Venturi et al. to be submitted). The GMRT is excellent for imaging diffuse extended emission in crowded fields, allowing accurate subtraction of individual sources to properly image diffuse large scale emission.

A 781 was observed for a total of 8 hours, using the upper and lower side band (USB and LSB, respectively), left and right polarization, for a total observing bandwidth of 32 MHz. The data were collected in spectral-line mode with 128 channels/band, leading to a spectral resolution of 125 kHz/channel. The USB and LSB datasets were calibrated and reduced individually using the NRAO Astronomical Image Processing System (AIPS) package. Beyond the normal flagging of bad baselines, antennas and time ranges, a very accurate editing was carried out to identify and remove those data affected by radio frequency interference (RFI). The bandpass calibration was performed using the flux density calibrator (3C 147). Due to strong RFI in the LSB dataset, only the upper portion of the band was used in the final imaging. Self-calibration and imaging were carried out using the same approach described in Macario et al. (2010) for A 697. We estimate that amplitude residual calibration errors are of the order of $\sim 8\%$.

We produced images in the resolution range from $11.6'' \times 9.2''$ to $40'' \times 37.0''$, with a 1σ noise $\sim 0.15\text{--}0.40 \text{ mJy beam}^{-1}$ going from high to low resolution. We finally im-

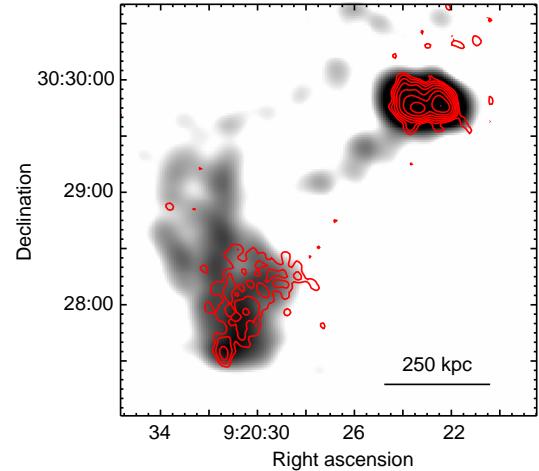


Figure 2. GMRT 610 MHz contours in A 781 overlaid on the GMRT 325 MHz emission. The resolution of the 610 MHz image is $6'' \times 5''$, contours start at $\pm 0.25 \text{ mJy beam}^{-1}$ ($\sim 3\sigma$) and are spaced by a factor of 2. The 325 MHz grey scale image is the same as the left panel in Fig. 1.

aged the cluster at the resolution of $61.6'' \times 51.9''$ reaching the noise of $1\sigma \sim 1 \text{ mJy beam}^{-1}$.

2.2 The peripheral candidate relic

Figure 1 shows the cluster radio emission at full and low resolution, overlaid on the optical and X-ray emission respectively. Beyond the individual sources, labelled S1 to S6 in the left panel (all resolved at this resolution), the candidate relic is the most striking feature in the A 781 field. As clear from Fig. 2, the source is much more extended at 325 MHz, compared to the 610 MHz image, with a largest angular size LAS $\sim 2'$ (i.e. $\sim 790 \text{ kpc}$). Its radio brightness is peaked in the southernmost part of the source, which is also edge brightened, in agreement with the 610 MHz images. The flux density at 325 MHz is $S_{325 \text{ MHz}} = 93.3 \pm 7.5 \text{ mJy}$, fairly consistent at all resolutions. The corresponding radio power is $P_{325 \text{ MHz}} = 2.61 \times 10^{25} \text{ W Hz}^{-1}$. The flux density in the 610 MHz image does not increase even integrating over the same extent imaged at 325 MHz. As mentioned in V08, the source is well visible on the NVSS at 1.4 GHz.

We looked into the NRAO VLA data archive in search for observations at higher frequencies. Two short observations exist, one at 1.477 GHz (C configuration, project AM469 observed on 15/03/1995), the second at 1.398 GHz (D configuration, project AO48 observed on 04/05/1984). We re-analyzed both datasets, and the resulting L-band VLA images are shown in Fig. 3 overlaid on the 325 MHz cluster field. The flux density of the candidate relic is consistent with the measurement from the NVSS and amounts to $S_{1.4 \text{ GHz}} = 15.3 \pm 0.5 \text{ mJy}$. The spectral index in the range 325 MHz–1.4 GHz is $\alpha = 1.25 \pm 0.06$. The 610 MHz flux density ($S_{610 \text{ MHz}} = 32 \pm 2 \text{ mJy}$, V08) is slightly below the 325 MHz–1.4 GHz fit of the spectrum (by a factor of $\sim 20\%$). In V08 we discussed the missing flux for the diffuse radio emission of the 610 MHz GMRT Radio Halo Survey, and the missing flux in A 781 is within the limits of our analysis. We checked the flux density of the sources reported in

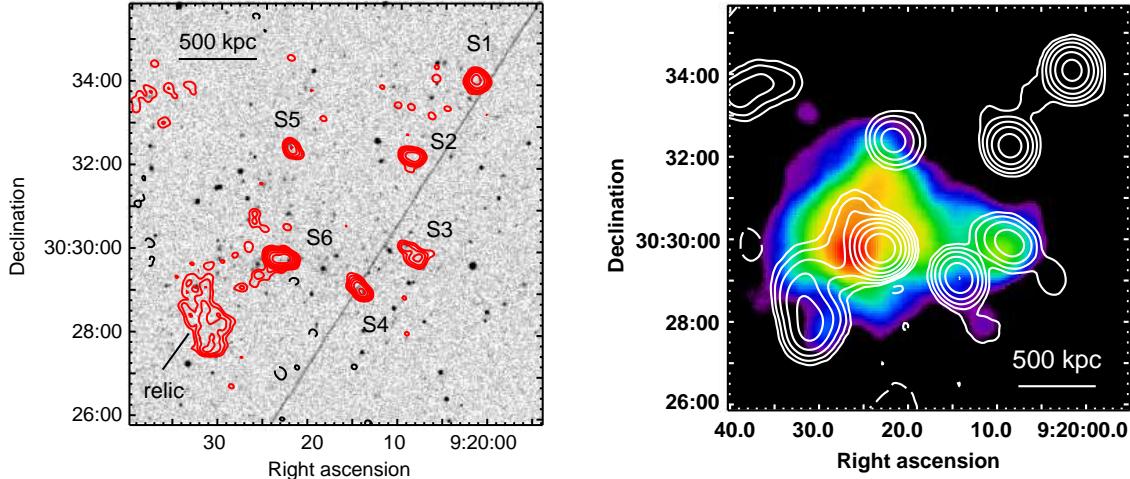


Figure 1. Left – GMRT 325 MHz radio contours of A 781 at the resolution of $11.6'' \times 9.2''$, position angle (p.a.) 73° , overlaid on the POSS-2 red plate. Contours (red positive, black negative) start at $\pm 0.45 \text{ mJy beam}^{-1}$ (3σ) and scale by a factor of 2. Individual radio galaxies are labelled from S1 to S6. Right – GMRT 325 MHz radio contours overlaid on the smoothed Chandra X-ray image. The resolution of the radio image is $40'' \times 37''$, p.a. -81° . Contours start at $1.2 \text{ mJy beam}^{-1}$ (3σ) and scale by a factor of 2.

Table 1 at 325 MHz, 610 MHz and 1.4 GHz (VLA-C array) using images of comparable resolution (of the order of $15''$). The flux density at 610 MHz is slightly underestimated in all cases, while the 325 MHz flux density values agree within 1σ with those estimated from the WENSS (WEsterbork Northern Sky Survey, Rengelink et al. 1997) image. The spectral index between 325 MHz and 1.4 GHz is consistent with nuclear emission from active galactic nuclei, i.e. $\alpha_{325\text{MHz}}^{1.4\text{GHz}}$ in the range $0.6 \div 0.8$ except for source S5, which has $\alpha_{325\text{MHz}}^{1.4\text{GHz}} \sim 1.4$.

An accurate analysis to thoroughly correct the 610 MHz flux density values is however beyond the scope of the present paper, and for this source we will assume $\alpha_{325\text{MHz}}^{1.4\text{GHz}} = 1.25$. We point out that this value is the average over the whole emission at 325 MHz, but the size of the emission at 1.4 GHz and at 610 MHz is considerably smaller. The spectral index in the common portion of the emission is $\alpha_{325\text{MHz}}^{1.4\text{GHz}} \sim 1$, allowing for the difficulties in “isolating” the 325 MHz flux density, while for the remaining part we estimate a lower limit $\alpha_{325\text{MHz}}^{1.4\text{GHz}} < 2$. Such sharp jump in the spectral index is intriguing, and worth it of further investigation.

The nature of this source remains uncertain. Its overall properties – morphology and linear size, location at the border of the X-ray emission in the direction of the secondary X-ray peak associated with CXOU J092053+302800, and the steep spectrum – coupled with the lack of an obvious optical counterpart, suggest that it might be a cluster radio relic (see also V08). However, the uneven distribution of the spectral index and the southern edge brightening at all frequencies are fairly unusual for relics, and we cannot rule out other possibilities, such as a tailed radio source.

2.3 Radio emission from the central cluster region

We checked for a possible extension of the relic towards the centre of A 781, and/or for a radio halo undetected at higher frequencies. We carried out flux density measurements over the inner ~ 1.5 Mpc around the cluster centre on the low

resolution images (from $30'' \times 30''$ to $62'' \times 52''$), and on a residual image obtained after subtraction of the clean components associated with the individual radio sources (left panel of Fig. 1 and Table 1). We imaged the “subtracted” u-v dataset using natural weighting to enhance any possible presence of diffuse emission. Our images are shown as colour scale and contours in Figure 4. The residual image (Fig. 4, right panel) clearly shows that the relic extends towards the centre of A 781, in the direction of the double source S6.

The flux density measured in a central region of ~ 1.5 Mpc in diameter, estimated by subtracting the contribution of the individual sources (S4, S6 and the relic) does not appreciably change with the resolution, and is of $\sim 15\text{--}20$ mJy. Considering that the total flux density of S4, S6 and the relic is 379.4 mJy (see Table 1), the residual flux density is $\sim 5\%$ of this value. A similar value is found by integrating the residual image over the same 1.5 Mpc region. We thus consider this value an upper limit for the flux density of possible diffuse emission at the centre of A 781, on a linear scale of the order of 1.5 Mpc.

The VLA L-band images we re-analyzed (Fig. 3) are in agreement with our 325 MHz results. The different frequencies of the two observations do not allow an accurate subtraction of the individual sources from the VLA-C to the VLA-D dataset, since spectral effects would result in residual flux density from the individual sources subtracted in the 1.398 GHz VLA-D array image. Moreover, the flatter spectrum of the individual sources compared to diffuse cluster sources (see Sect. 2.2 and Table 1) makes the source subtraction at 1.4 GHz more critical than at lower frequencies. Hence we simply compared the sum of the flux density of the individual sources S4, S6 and the relic to the total flux density of the L-band images integrating over the whole area encompassing them. No difference is detected in either images, and in both cases the values agree within $\lesssim 2\%$.

The results of our analysis disagree with Govoni et al. (2011), who recently claimed the detection of a radio halo (with flux 20–30 mJy at 1.4 GHz) using the same VLA

archival data. They also derived an upper limit to the flux density of the radio halo at 330 MHz (≤ 135 mJy) using an archive VLA observation, pointed 1.5° away from the cluster centre, and give an upper limit of $\alpha_{\text{VLA } 330 \text{ MHz}}^{\text{VLA } 1.4 \text{ GHz}} \leq 1.3$ to its spectral slope. Our 325 MHz observations are about 5 times more sensitive than those in Govoni et al., and rule out the presence of a halo in A 781 with flux density of 20–30 mJy at 1.4 GHz. The resulting spectral index, with our improved value of the 325 MHz residual flux density, would be $\alpha_{\text{GMRT } 325 \text{ MHz}}^{\text{VLA } 1.4 \text{ GHz}} \leq 0.5$ (using a conservative limit, $S_{325 \text{ MHz}} \leq 40$ mJy) which is definitely unphysical for diffuse cluster sources. We point out that one feature in the Govoni et al. residual image is the discrete source S3, which has an optical counterpart, as clear from the left panel of Fig. 1 and in V08; moreover, the sources labelled C and D in their paper are clearly extended in the direction of the residual emission.

3 IS THERE A RADIO HALO IN A 781?

A statistical connection between the dynamical state of massive clusters in the GMRT sample (V07 and V08) and the presence of radio halos has been derived by C10, confirming the picture where mergers switch-on radio halos in galaxy clusters. A 781 is one of the few outliers in the Cassano et al. diagrams, lying in the region of dynamically disturbed clusters, but with no detected radio halo at 610 MHz (V08).

The observations at 325 MHz presented in this Letter do not allow a firm detection of a radio halo in the central region (~ 1.5 Mpc) of A 781. If we consider a spectral index $\alpha \sim 1.3$ between 325–1400 MHz, the residual diffuse emission measured in our images, $S_{325 \text{ MHz}} \sim 20$ mJy, puts a conservative limit to the 1.4 GHz luminosity of a halo in A 781 $P_{1.4 \text{ GHz}} \leq 6 \times (S_{0.3} / 20) \times 10^{23} \text{ W Hz}^{-1}$ (where $S_{0.3}$ is the flux at 325 MHz in mJy).

Our results do not challenge the cluster merger–radio halo connection. On the basis of the $P_{1.4 \text{ GHz}}\text{--}L_X$ correlation, the expected 1.4 GHz radio luminosity of the halo is still consistent with our upper limit. As a matter of fact, the four known radio halos with radio power $\sim 10^{24}$ W Hz^{-1} hosted in clusters with X-ray luminosity $L_X \leq 5 \times 10^{44} \text{ erg s}^{-1}$ (i.e. A 2255, A 2256, Coma and A 754) are only detected at low redshift, $z \leq 0.1$. On the other hand, if we assume the 1.4 GHz luminosity recently claimed by Govoni et al. (2011), the halo would lie about an order of magnitude above the radio/X-ray correlation. Incidentally, in their paper the halo is found consistent with that correlation simply because the authors use the old overestimated X-ray luminosity for A 781, as given in the eBCS catalogue (see Sect. 2).

Assuming that the residual emission at the centre of A 781 does reveal the presence of an underlying very low brightness radio halo, the combination of 325 and 610 MHz provide further hints on its spectral properties. The 610 MHz upper limit and the residual emission at 325 MHz imply a spectral index of the emission steeper than $\alpha \geq 2.5$. Even accounting for the uncertainty in the 610 MHz upper limit, which depends on the assumptions made on the unknown brightness distribution (see Brunetti et al. 2007 and V08), our experience shows that radio halos with $S_{610 \text{ MHz}} = 10\text{--}20$ mJy are well imaged in the GMRT Radio Halo Survey

Table 1. GMRT 325 MHz flux density of the discrete radio sources and spectral properties.

Source name	RA ^a (h,m,s)	DEC ^a (deg, ', '')	Speak (mJy/b)	S_{tot}^b (mJy)	α_{325}^{1477}
S1	09 20 01.6	+30 34 06	27.3 ± 2.2	73.7 ± 5.9	0.75
S2	09 20 08.3	+30 21 15	17.2 ± 1.4	41.6 ± 3.3	0.58
S3	09 20 07.9	+30 29 51	5.3 ± 0.4	23.2 ± 1.9	-
S4	09 20 14.1	+30 29 01	23.8 ± 1.9	50.8 ± 4.1	0.77
S5	09 20 22.1	+30 32 25	8.9 ± 0.7	16.6 ± 1.3	1.41
S6	09 20 22.7	+30 29 47	77.8 ± 6.2	225.3 ± 18.0	0.77
Relic	09 20 31.2	+30 27 35	5.7 ± 0.4	93.3 ± 7.5	see text

Flux density values taken from the image shown in the left panel of Fig. 1 and 4 ($11.6'' \times 9.2''$) after primary beam correction.

^a: coordinates of the radio peak; ^b: total flux density measured using the AIPS task `TVSTAT`; ^c: Spectral index derived from flux density measurements at the resolution of $17'' \times 11''$ at 325 MHz and of $16'' \times 13''$ at 1477.40 MHz.

(i.e. A 697 at a similar redshift, V08). This suggests a conservative upper limit of $S_{610 \text{ MHz}} < 10$ mJy, which would still imply a steep spectrum halo, i.e. $\alpha > 1.5$. It is noteworthy that statistical expectations based on the turbulent re-acceleration model show that radio halos with steep spectra should be quite common in merging clusters with masses $\sim 10^{15} \text{ M}_\odot$, similar to that of A 781 (Cassano et al. 2006).

4 SUMMARY AND CONCLUSIONS

We have presented deep GMRT 325 MHz observations of the unrelaxed and luminous cluster A 781, which is a noticeable outlier in the quantitative correlations connecting cluster mergers and the presence of a radio halo (C10). Our images show that the peripheral diffuse source is the dominant radio feature of the cluster, and only residual emission at the level of $S_{325 \text{ MHz}} \sim 15\text{--}20$ mJy is found in a region of ~ 1.5 Mpc around the cluster centre (implying a conservative flux density limit of $S_{325 \text{ MHz}} \sim 30\text{--}40$ mJy). This value improves the upper limit given in Govoni et al. (2011) by almost a factor of 5, and rules out the claim of a detection of a radio halo at 1.4 GHz (Govoni et al. 2011) on the basis of simple spectral considerations.

With our data we cannot confirm the presence of a radio halo at the centre of A 781. If the 325 MHz residual emission is real, then it might trace an underlying halo with steep spectrum. Future high sensitivity observations at lower frequencies combined with deeper observations at 610 MHz will allow us to clarify the nature of the residual emission.

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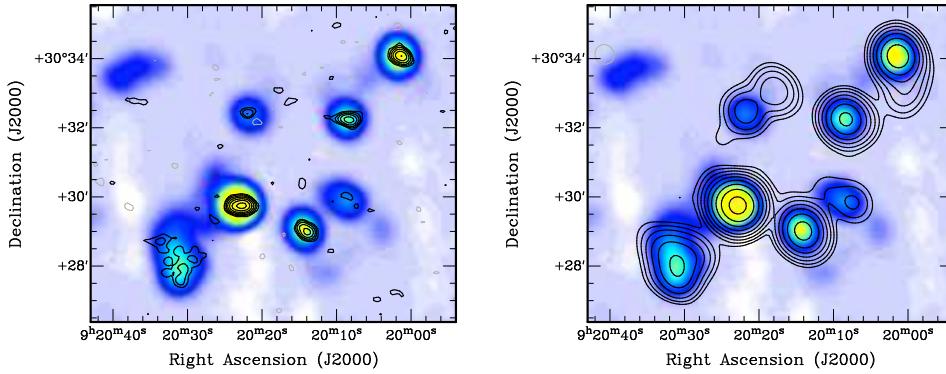


Figure 3. Left – VLA-C 1477 MHz contours at the resolution of $16.5'' \times 13.1''$, in p.a. -86.4° overlaid on the $40'' \times 37''$ 325 MHz GMRT image (same as Fig. 1, right panel). Contours start at $\pm 0.45 \text{ mJy beam}^{-1}$ (3σ) and are spaced by a factor of 2. Right – VLA-D 1398 MHz contours of A 781 at the resolution of $47.1'' \times 43.5''$, in p.a. 18.1° overlaid on the same 325 MHz GMRT image. Contours start at $\pm 0.21 \text{ mJy beam}^{-1}$ (3σ , where σ is the confusion limit) and are spaced by a factor of 2.

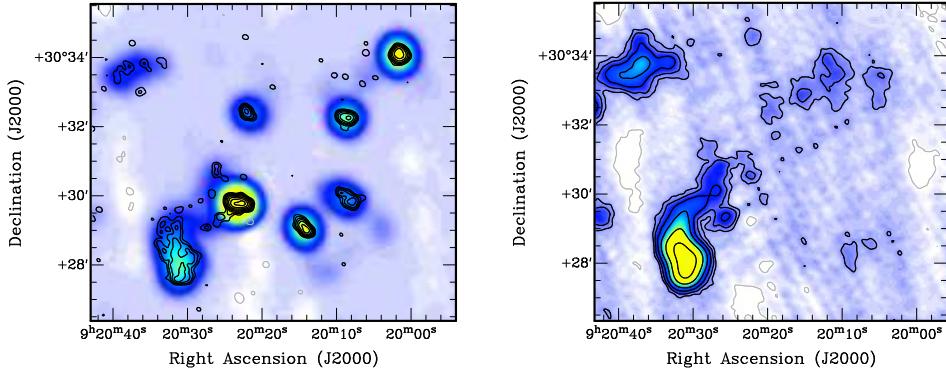


Figure 4. Left – GMRT 325 MHz image of A 781 at the resolution of $40'' \times 37''$, in p.a. 12.6° (blue scale) with $11.6'' \times 9.2''$ contours overplotted. Contours are spaced by a factor of 2 starting from $\pm 0.45 \text{ mJy beam}^{-1}$. Right – GMRT 325 MHz residual image at the resolution of $30'' \times 30''$ with contours overlaid. Contours start from $\pm 0.5 \text{ mJy beam}^{-1}$ ($\sim 2\sigma$) and are spaced by a factor of 2.

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